Open Channel

by Joseph J. Carr

Fiber Optic Technology — Part 1

Fiber optics is the latest in communications and instrumentation technology, at least as far as the "wiring" is concerned. Briefly stated, *fiber optics is the passing of light through a plastic or glass fiber so that it can be directed to a specific location.* If the light is encoded *(modulated)* with an information signal, then that signal is transmitted over the optical path. In this month's column, we will take a look at fiber optic technology.

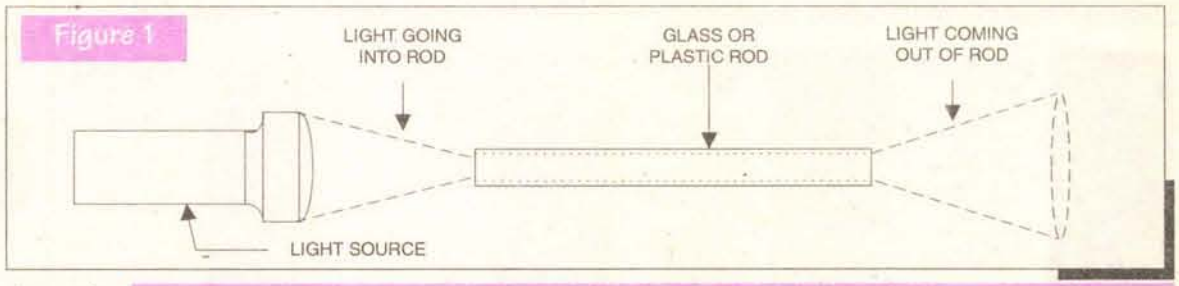
There are many advantages to the optical fiber communications or data link, including:

* Very high bandwidth (accommodates video signals, multiple voice channels, or high data rate computer communications).
* Very low weight and small size.
* Low loss compared with other media.
* No electromagnetic interference (EMI).
* High degree of electrical isolation.
* Explosion proof.
* Good data security.
* Improved "fail-safe" capability.

The utility of the high-bandwidth capability of the fiber optical data link is that it can handle a tremendous amount of electronically transmitted information simultaneously. For example, it can handle more than one video signal (which typically requires 500 kHz to 6 MHz of bandwidth, depending on resolution). Alternatively, it can handle a tremendous number of voice communication telephone channels. A high-speed computer data communications capability is also possible. Either a few channels can be operated at extremely high speeds, or a larger number of low-speed parallel data channels are available. Fiber optics is so significant that one can expect to see it proliferate in the communications industry for years to come.

The light weight and small size, coupled with relatively low loss, gives the fiber optic communications link a great economic advantage when large numbers of channels are contemplated. To obtain the same number of channels using coaxial cables or "paired wires," the system would require a considerably larger — and heavier — infrastructure.

Figure 1



Fiber optic principles were first noted in the early 1870s when John Tyndall introduced members of Britain's Royal Society to his experimental apparatus.

Electromagnetic Interference (EMI) and System Safety

Electromagnetic interference (EMI) has been an annoying factor in electronics since Marconi and DeForest interfered with each other in radio trials for the Newport Yacht Races prior to the turn of the 20th-century.

Today, EMI can be more than merely annoying; it can cause tragic accidents. For example, airliners are operated more and more from digital computers. Indeed, one airline copilot recently quipped (about modern aircraft) that one doesn't need to know how to fly anymore, but one does need to be able to type on a computer keyboard at 80 words per minute. This points out just how dependent aircraft have become on modern digital computers and intercommunication between digital devices. If a radio transmitter, radar, or electrical motor is near one of the intercommunications lines, it would be possible to either introduce false data or corrupt existing data unless the proper precautions were taken in the design. Because the EMI is caused by electrical or magnetic fields coupling between electrical cables, optical fibers, being free of such fields, produce dramatic freedom from EMI.

Electrical isolation is required in many instrumentation systems either for user safety, or to avoid electronic circuit damage. In some industrial processes, high electrical voltages are used, but the electronic instruments used to monitor the process are both low-voltage and ground referenced. As a result, the high voltage can damage the monitor instruments. In fiber optical systems, it is possible to use an electrically floating sensor, and then transmit the data over a fiber link to an electrically grounded, low-voltage computer, instrument, or control system.

Optical fibers can transmit light beams generated in non-contacting electronic circuits, making fiber optic systems ideal for use around flammable gases or fumes, nuclear power generators, and other hazardous environments. Regular mechanical switches or relays arc on contact or release, and those sparks may ignite flammable gases or fumes. Occasional operating room explosions in hospitals occurred prior to 1980, and electrical arcs in switches have caused gasoline station explosions.

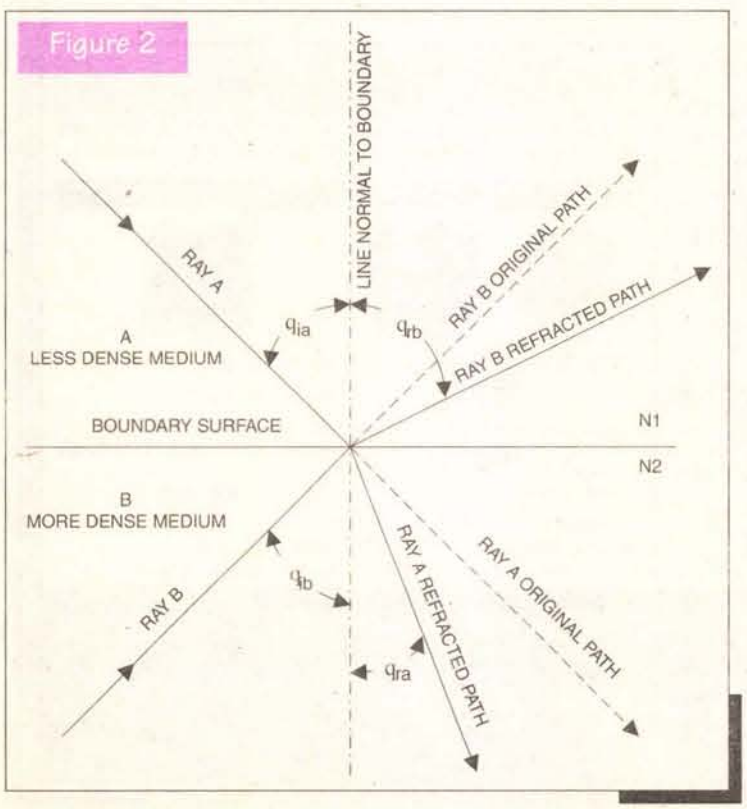
System security is enhanced because optical fibers are difficult to tap. An actual physical connection must be made to the system, resulting in a detectable power loss. In wire systems, capacitive or inductive pickups can acquire signals with less than total physical connection. Similarly, a system is more secure in another sense of the word because the fiber optic transmitters and receivers can be designed "fail safe" so that one fault does not take down the system.

Fiber Optic Principles

Fiber optic principles were first noted in the early 1870s when John Tyndall introduced members of Britain's Royal Society to his experimental apparatus (Figure 1). An early, but not very practical, color television system patented by J. L. Baird used glass rods to carry the color information. By 1966, C. Hockham and C. Kao demonstrated a system in which light beams carried data communications via glass fibers. The significant fact that made the Hockham/Kao system work was the reduction of loss in the glass dielectric material to a reasonable level. By 1970, practical fiber optic communications were theoretically possible.

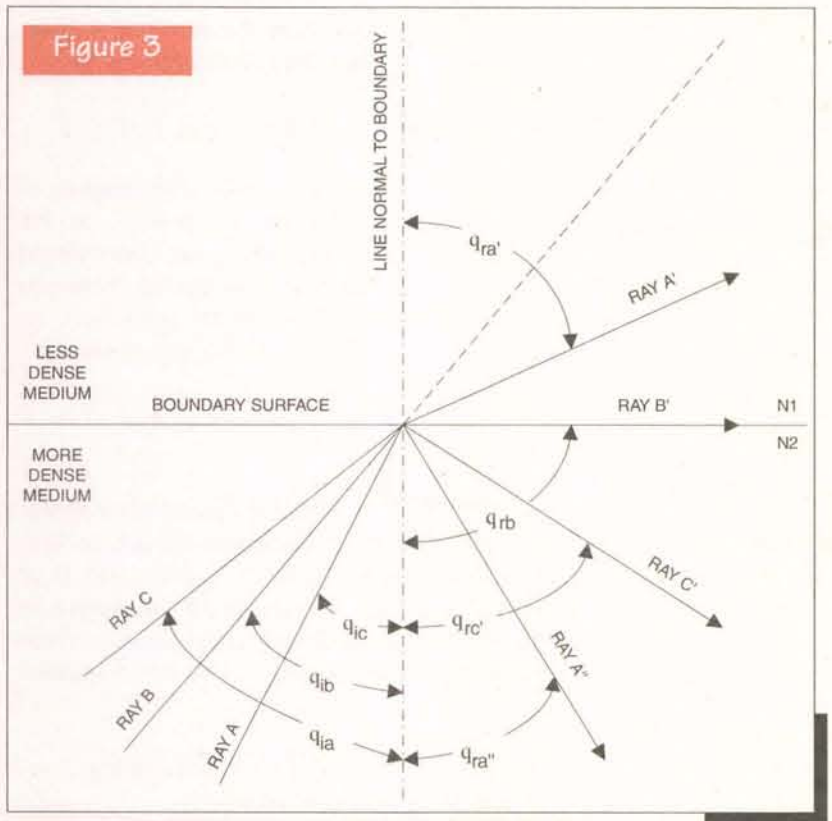
Before examining fiber optic technology, it might be useful to review some of the basics of

Figure 2



Refraction is the change in direction of a light ray as it passes across the boundary surface, or "interface," between two media of differing indices of refraction.

Figure 3



Of particular concern in fiber optics is the situation of a light ray passing from one medium to a less dense medium.

optical systems as applied to fiber optics.

Review of the Basics

The *index of refraction*, or *refractive index*, is the ratio of the speed of light in a vacuum to the speed of light in the medium of interest (glass, plastic, water); for practical purposes, the speed of light in air is close enough to its speed in a vacuum to be considered the same. Mathematically, the index of refraction, n, is:

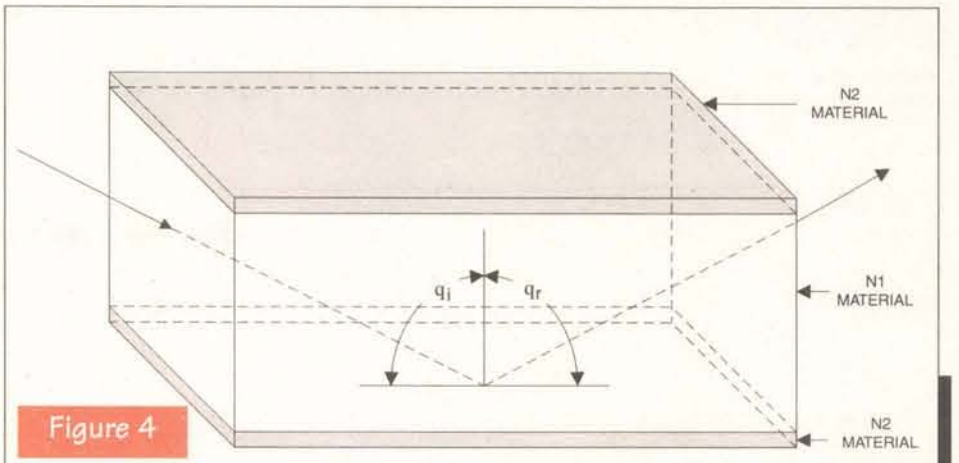
$$n = \frac{c}{v_m}$$

where,

c is the speed of light in a vacuum (3×10^8 m/s),

v_m is the speed of light in the medium.

Figure 4



An optical fiber is similar to a microwave waveguide, and an understanding of waveguide action is useful in understanding fiber optics.

Refraction is the change in direction of a light ray as it passes across the boundary surface, or "interface," between two media of differing indices of refraction. In Figure 2, two materials, N1 and N2, have indices of refraction n_1 and n_2, respectively. In this illustration, N1 is optically less dense than N2. Consider incident light ray A, approaching the interface through the less dense medium (N1 → N2). As it crosses the interface it changes direction toward a line normal (at a right angle) to the surface. Ray B approaches the interface through the denser medium (N2 → N1). In this case, the light ray is similarly refracted from its original path, but the direction of refraction is *away* from the normal line.

In refractive systems, the angle of refraction is a function of the ratio of the two indices of refraction, i.e., it obeys *Snell's law:*

$$n_1 \sin \theta_i = n_2 \sin \theta_r$$

or,

$$\frac{n_1}{n_2} = \frac{\sin \theta_r}{\sin \theta_i}$$

where,

θ_i is the angle of incidence,

θ_r is the angle of refraction.

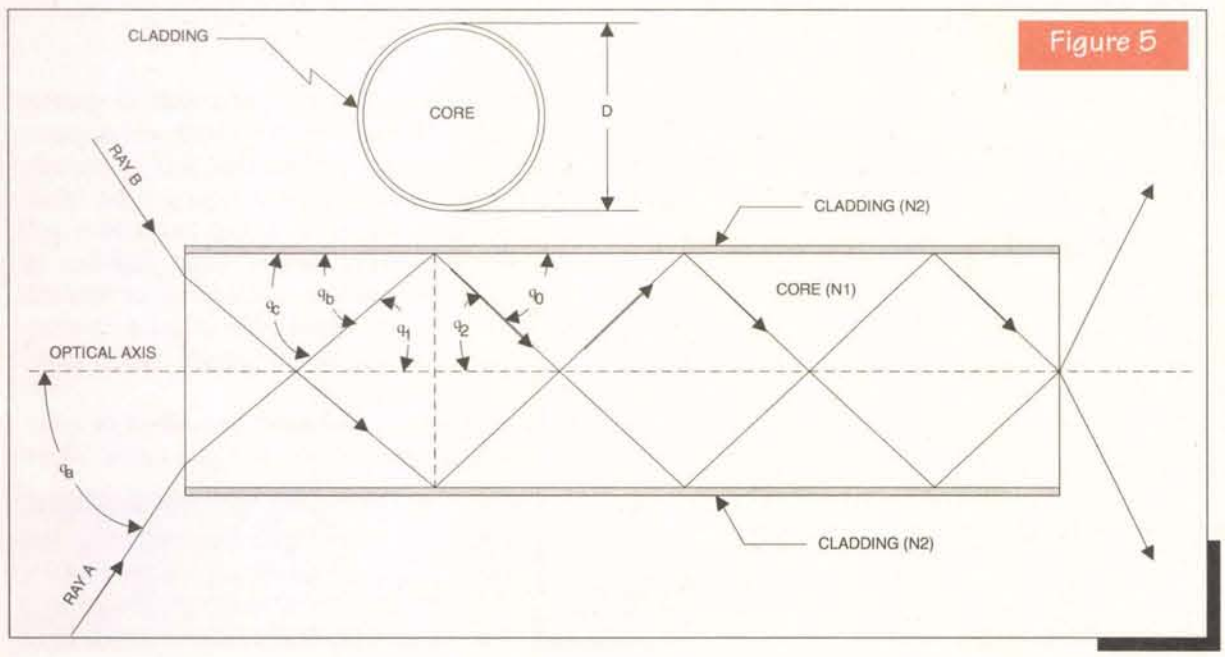
Of particular concern in fiber optics is the situation of a light ray passing from one medium to a less dense medium. This can be illustrated with either a water-to-air system, or a system in which two different glasses, having different indices of refraction, are interfaced. This situation is shown in Figure 2 with Ray B.

Figure 3 shows a similar system with three different light rays approaching the same point on the interface from three different angles. (θ_{ia}, θ_{ib}, and θ_{ic}, respectively). Ray A approaches at a *subcritical angle*, θ_{ia}, so it will split into two portions (A' and A"). The reflected portion, A', contains a relatively small amount of the original light energy, and may indeed be nearly indiscernible. The major portion, A", of the light energy is transmitted across the boundary, and refracts at an angle $\theta_{ra'}$ in the usual manner.

Light Ray B, on the other hand, approaches the interface at a *critical angle*, θ_{ib}, and is refracted along a line that is orthogonal to the normal line; that is, it travels along the interface boundary surface. This angle is labeled θ_c in optics textbooks.

Finally, Ray C approaches the interface at an angle greater than the critical angle, known as the *supercritical angle*. None of this ray is transmitted, but rather it is turned back into the original medium. This phenomenon is called *total internal reflection* (TIR). It is this phenomenon that allows fiber optics to work. TIR is called total internal *reflection*, but it is actually a refraction phenomenon.

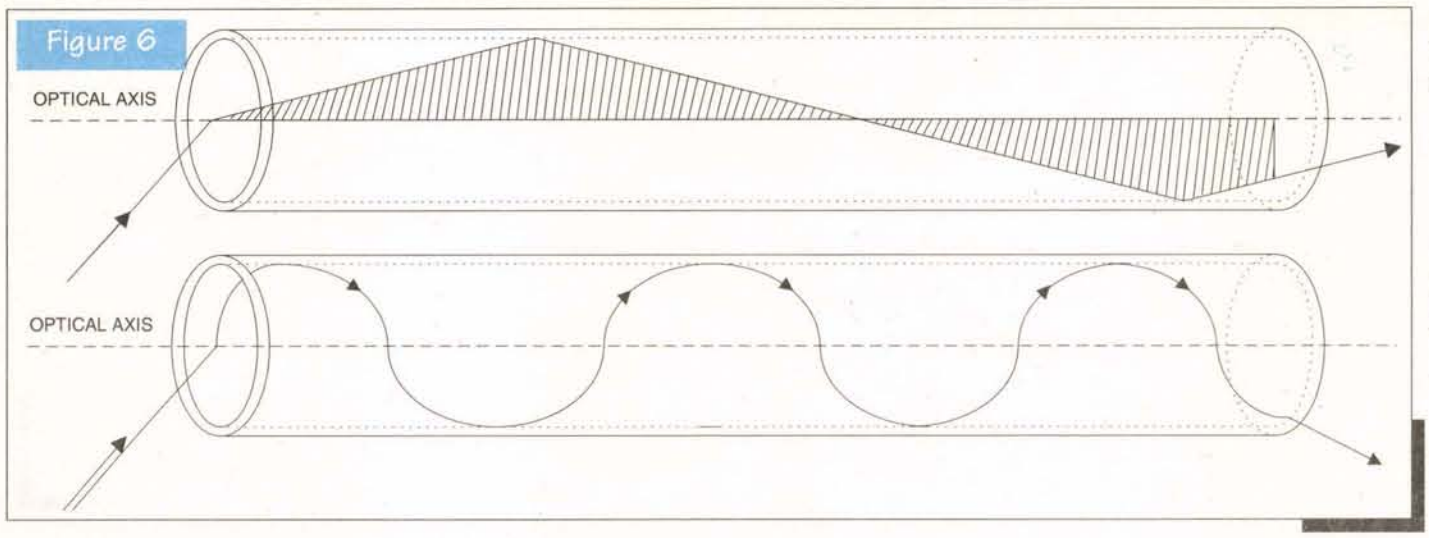
Figure 5



Fiber Optics

An optical fiber is similar to a microwave *waveguide*, and an understanding of waveguide action is useful in understanding fiber optics. A schematic model of an optical fiber is shown in Figure 4. A slab of material (N1) is sandwiched between two slabs of a less dense material (N2). Light rays that approach from a supercritical angle are totally internally reflected from the two interfaces (N2 → N1 and N1 → N2). Although only one "bounce" is shown in the illustration, the ray will be subjected to successive TIR reflections as it propagates

Fiber Optic Technology — Part 1



through the N1 material. The proportion of light energy that is reflected through the TIR mechanism is on the order of 99.9 percent, which compares quite favorably with the 85 to 96 percent typically found with plane mirrors.

Fiber optic lines are not rectangular, but cylindrical, as shown in Figure 5. The illustrated components are called *clad optical fibers* because the inner core is surrounded by a less dense layer called *cladding*. Shown in Figure 5 are two rays, each of which is propagated into the system at supercritical angles. These rays will propagate through the cylindrical optical fiber with very little loss of energy.

There are actually two forms of propagation. The minority form, called *meridional rays*, are easier to understand and mathematically modeled in textbooks because all rays lie in a plane with the optical axis (Figure 6A). The more numerous *skew rays* follow a helical path, so are somewhat more difficult to discuss (Figure 6B).

The *cone of acceptance* of the optical fiber is a conical region centered on the optical axis (Figure 7). The *acceptance angle* θ_a is the critical angle for the transition from air ($n = n_a$) to the core material ($n = n_1$). The ability to collect light is directly related to the size of the acceptance cone, and is expressed in terms of the *numerical aperture* (NA), which is:

$$NA = \sin \theta_a$$

The refraction angle of the rays internally, across the air-n_1 interface, is given by Snell's law:

$$\theta_{b1} = \arcsin\left(\frac{n_a \sin \theta_a}{n_1}\right)$$

It can be shown that:

$$\theta_{a1} = \theta_{a2}$$

$$\theta_{b1} = \theta_{b2}$$

$$\theta_{a1} = \frac{\theta_a}{n_1}$$

In terms of the indices of refraction of the ambient environment outside the fiber, the core of the fiber, and the cladding material, the numerical aperture is given by:

$$NA = \sin \theta_a = \frac{1}{n_a}\sqrt{(n_1)^2 - (n_2)^2}$$

If the ambient material is air, then the numerical aperture equation reduces to:

$$NA = \sqrt{(n_1)^2 - (n_2)^2}$$

Internally, the angles of reflection θ_{a1} and θ_{a2}, at the critical angle, are determined by the relationship between the indices of refraction, n_1 and n_2, of the two materials:

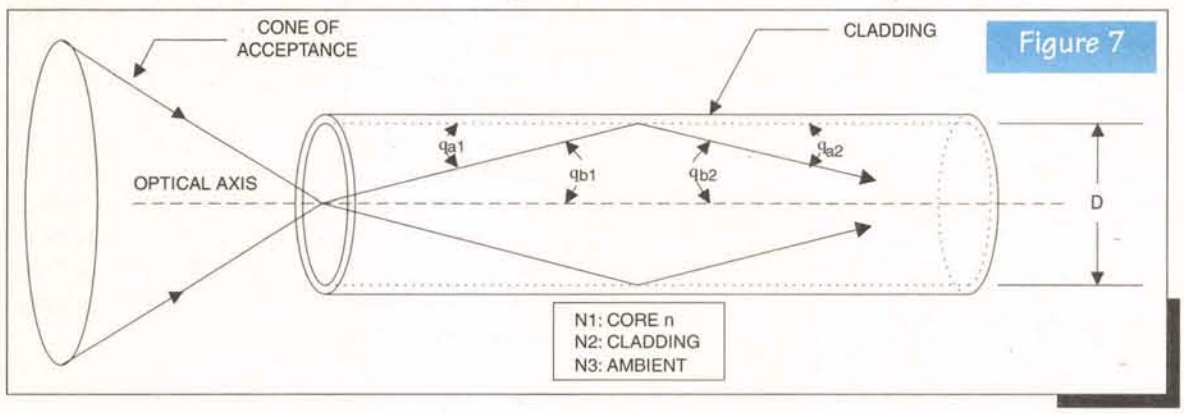
$$\theta_{a1} = \frac{\arcsin\sqrt{(n_1)^2 - (n_2)^2}}{n_1}$$

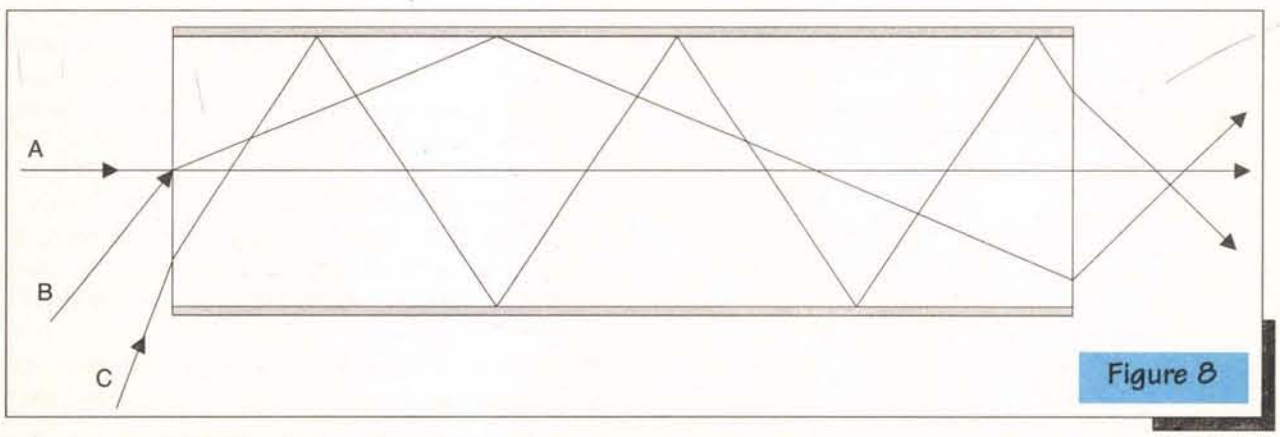
Typical optical fiber materials have numerical apertures of 0.1 to 0.5; typical multimode fibers have diameters D of 25 μm to 650 μm. The ability of the device to collect light is proportional to the square of the numerical aperture multiplied by the diameter:

$$\zeta \propto (NA \times D)^2$$

where,

ζ is the relative light collection ability,
NA is the numerical aperture,
D is the fiber diameter.





Intermodal Dispersion

When a light ray is launched in an optical fiber, it can take any of a number of different paths, depending in part on its launch angle (Figure 8). These paths are known as *transmission modes*, and vary from very-low order modes parallel to the optical axis of the fiber (Ray A), to the highest-order mode close to the critical angle (Ray C); in addition, there are many paths between these two limits. An important feature of the different modes is that the respective path lengths vary tremendously, being shortest with the low-order modes and longest with high-order modes. If an optical fiber has only a single core and single layer of cladding, it is called a *step index* fiber because the index of refraction changes abruptly from the core to the cladding. The number of modes, N, that can be supported is given by:

$$N = \frac{1}{2}\left(\frac{\pi D [NA]}{\lambda}\right)^2$$

Any fiber with a core diameter D greater than about 10 wavelengths (10λ) will support a very large number of modes, and is typically called a *multimode fiber*. A typical light beam launched into such a step index fiber will simultaneously find a large number of modes available to it. This may or may not affect analog signals, but it has a deleterious effect on digital signals called *intermodal dispersion*.

Figure 9 illustrates the effect of intermodal dispersion on a digital signal. When

When a light ray is launched in an optical fiber, it can take any of a number of different paths, depending in part on its launch angle

Fiber Optic Technology — Part I

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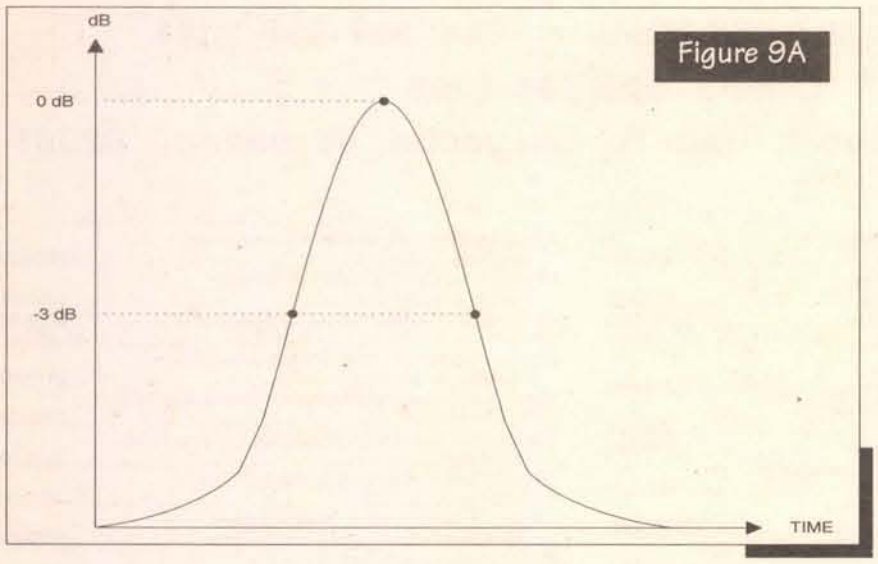

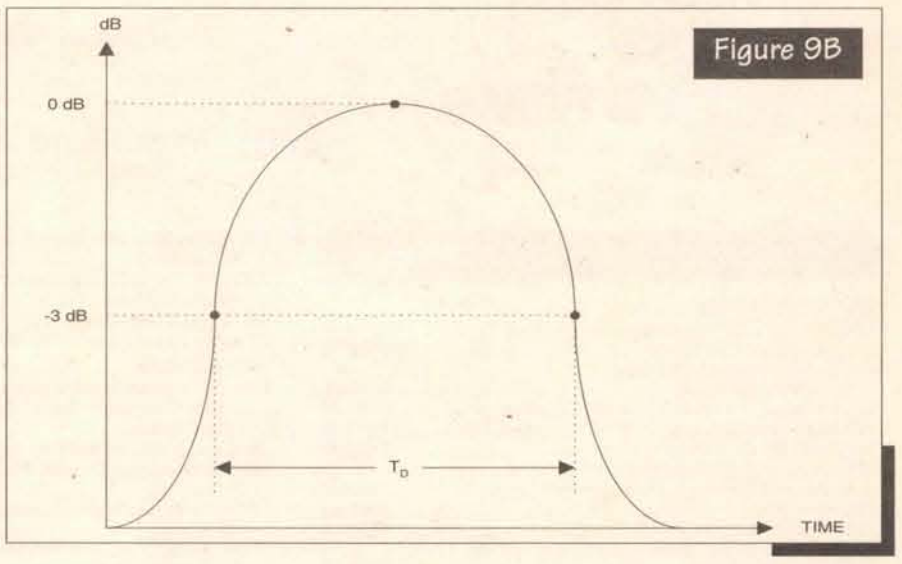

a short-duration light pulse (Figure 9A) is applied to an optical fiber that exhibits a high degree of intermodal dispersion, the received signal (9B) is dispersed, or "smeared," over a wider area. At slow data rates, this effect may prove negligible because the dispersed signal can die out before the next pulse arrives. But at high speeds, the pulses may overrun each other (Figure 10), producing an ambiguous signal that exhibits a high data error rate.

Intermodal dispersion is usually measured relative to the widths of the pulses at the -3 dB (half-power) points. In Figure 9, the time between -3 dB points on the incident pulse transmitted into the optical fiber is T, while in the received pulse the time between -3 dB points is T_d. The dispersion is expressed as the difference, or:

$$Dispersion = T - T_d$$

A means for measuring the dispersion for any given fiber optic element is to measure the dispersion of a Gaussian (normal distribution) pulse at those -3 dB points. The cable is then rated in nanoseconds of dispersion per kilometer of fiber (ns/km).

The bandwidth (BW) of the fiber, an expression of data rate in MegaHertz per kilometer (MHz/km), can be specified from knowledge of the dispersion, using the expression:

$$BW\ (MHz/km) = \frac{310}{Disp.(ns/km)}$$

Next Month ...

Next month, we will look at the types of defects and losses that one finds in fiber optic systems. **NV**

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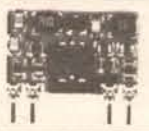

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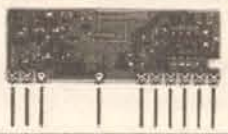

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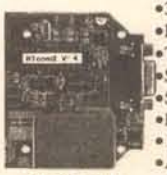

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by Joseph J. Carr

Fiber Optic Technology — Part 2

Last month, we introduced you to fiber optic technology, and progressed through the dispersion problem. A solution to the dispersion problem is to build an optical fiber with a continuously varying index of refraction that decreases with increasing distance from the optical axis.

While such smoothly varying fibers are not easy to build, it is possible to produce an optical fiber with layers of differing indices of refraction (Figure 1). Such a fiber is known as a graded index fiber.

The overall index of refraction determines the numerical aperture, and is taken as the average of the different layers.

With graded index fibers, the velocity of propagation of the light ray in the material is faster in the layers away from the optical axis than in the lower layers. As a result, a higher-order mode wave will travel faster than a wave in a lower order.

The number of modes available in the graded index fiber is:

$$N = \frac{1}{4}\left(\frac{\pi D [NA]^2}{\lambda}\right)$$

Some cables operate in a critical mode, designated HE_{11} (to mimic microwave terminology), in which the cable is very thin compared with multimodal cables. As the diameter of the core decreases, so does the number of available modes, and eventually the cable becomes single-mode (sometimes, especially in the United Kingdom, called monomodal). If the core is as small as three to five mm, then only the HE11 mode becomes available. The critical diameter required for single-mode operation is:

$$D_{crit} = \frac{2.4\,\lambda}{\pi\,[NA]}$$

Because a single-mode cable reduces the number of available modes, it also reduces intermodal dispersion. Thus, the monomode fiber is capable of extremely high data rates or analog bandwidths.

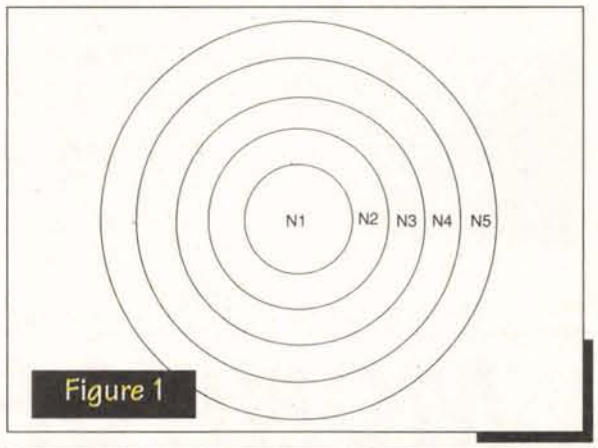

Figure 1

While such smoothly varying fibers are not easy to build, it is possible to produce an optical fiber with layers of differing indices of refraction

LOSSES IN FIBER OPTIC SYSTEMS

Understanding and controlling losses in fiber optic systems is integral to making the system work properly. Before examining the sources of such losses, we will briefly examine the vocabulary used to describe losses in the system, as well as the gains of the electronics systems used to process the signals applied to, or derived from, the fiber optic system. This vocabulary uses the decibel (introduced earlier) in the system of measurement.

In order to analyze systems using simple addition and subtraction — rather than multiplication and division — a little math trick is used on the ratio. We take the base-10 logarithm of the ratio, and then multiply it by a scaling factor (either 10 or 20). For voltage systems, such as our voltage amplifier, the expression becomes:

$$dB = 20 \log\left(\frac{V_o}{V_{in}}\right)$$

The fact that the quantity represented is a gain is indicated by the plus sign. If the quantity represented a loss ($V_o < V_{in}$), then the sign of the result would be negative. Working the problem above for the ratio 0.5/6 results in a loss of -21.6 dB. The numerical result for a loss using the same voltages is the same as for a gain, but the sign is reversed.

Despite the fact that the ratio has been converted to a logarithm, the decibel is nonetheless nothing more than a means for expressing a ratio. Thus, a voltage gain of 12 can also be expressed as a gain of 21.6 dB. A similar expression can be used for current amplifiers, where the gain ratio is I_o/I_{in}:

$$dB = 20 \log\left(\frac{I_o}{I_{in}}\right)$$

For power measurements — which are what is important in light and fiber optic systems — a modified expression is needed in order to account for the fact that power is proportional to the square of the voltage or current:

$$dB = 10 \log\left(\frac{P_o}{P_{in}}\right)$$

We now have three basic equations for calculating decibels: one each for current ratios, voltage ratios, and power ratios. The usefulness of decibel notation is that it can make nonlinear power and gain equations into linear additions and subtractions. Figure 2A shows the losses in fiber optics for the normalized case in terms of output power, and Figure 2B shows the loss in decibels.

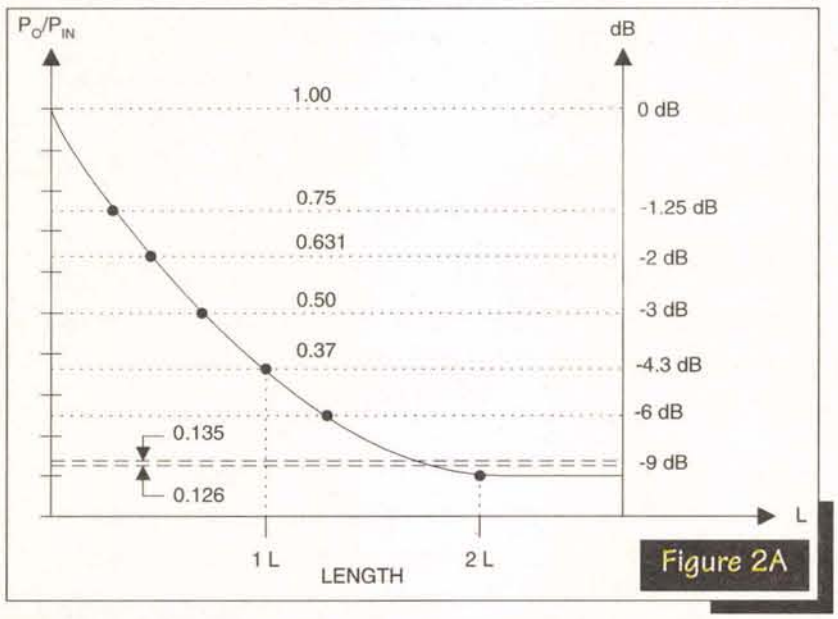

Figure 2A

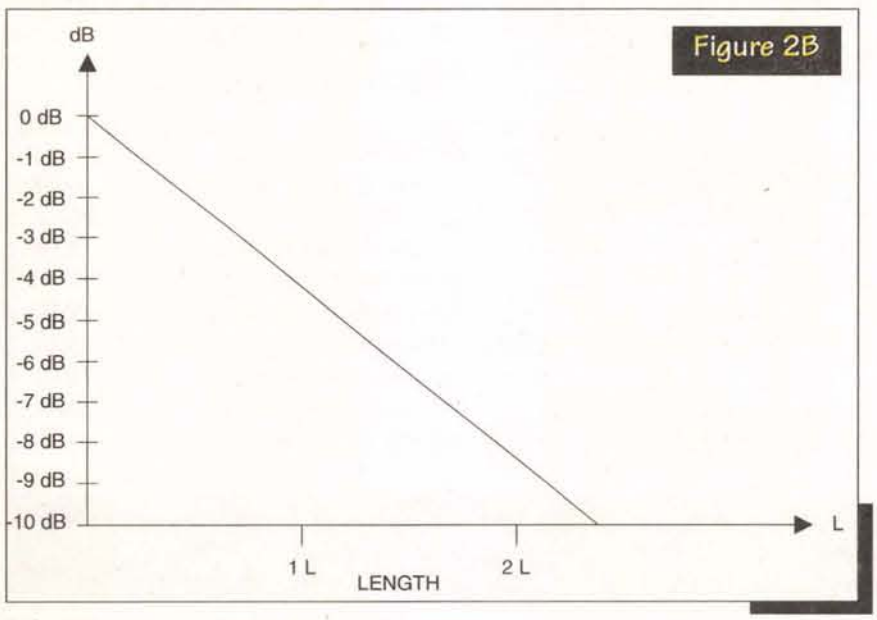

Figure 2B

Figure 2A shows the losses in fiber optics for the normalized case in terms of output power, and Figure 2B shows the loss in decibels.

Mechanisms for Loss

There are several mechanisms for loss in fiber optic systems. Some of these are inherent in any optical system, while others are a function of the design of the specific system being considered.

Defect Losses. Figure 3 shows several possible sources of loss due to defects in the fiber

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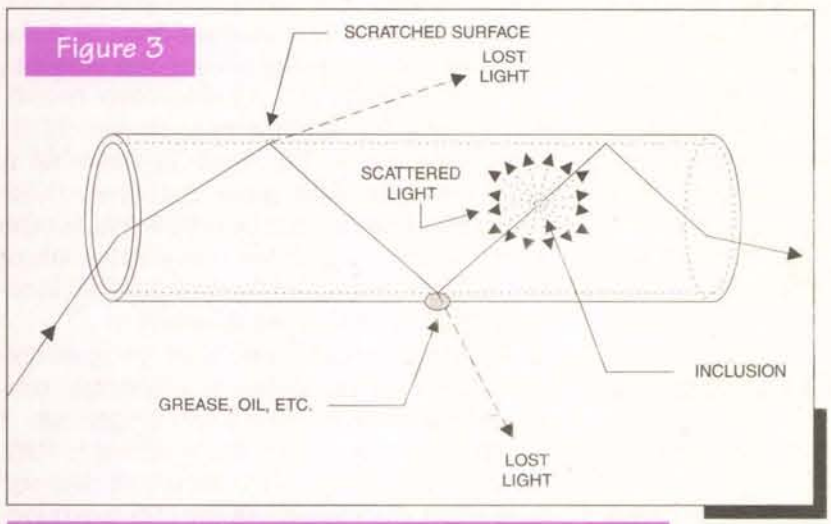


Figure 3

Nicks or scratches that breach the integrity of the surface will allow light to escape.

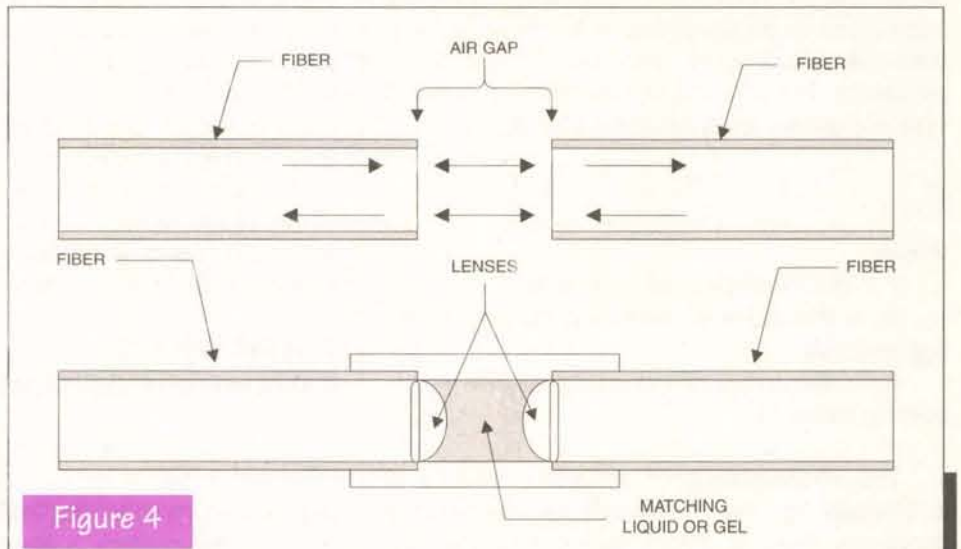


Figure 4

Fresnel Reflection Losses. occur at the interface of an optical fiber with air

itself. In unclad fibers, surface defects (nicks or scratches) that breach the integrity of the surface will allow light to escape. Also in unclad fibers, grease, oil, or other contaminants on the surface of the fiber may form an area with an index of refraction different from what is expected, causing the light direction to change. If the contaminant has an index of refraction similar to that of glass, then it may act as if it were glass and cause loss of light to the outside world.

Finally, there is always the possibility of inclusions: objects, specks, or voids in the material making up the optical fiber. Inclusions can affect both clad and unclad fibers. When light hits an inclusion, it tends to scatter in all directions, causing a loss. Some of the light rays scattered from the inclusion may recombine either destructively or constructively with the main ray, but most do not.

Inverse Square Law Losses. In all optical systems, there is the possibility of losses due to spreading of the beam. Light power per unit area is inversely proportional to the square of the distance ($1/D_2$) from the source. If you shine a flashlight at a wall from a distance of one meter, and measure the power per unit area at the wall, and then move the light back to twice the distance and measure again, you will find that the power has dropped to one-fourth of its original level.

Transmission Losses. These losses are due to light that is caught in the cladding material of clad optical fibers. This light is either lost to the outside, or is trapped in the cladding layer and is thus not available to be propagated in the core.

Absorption Losses. This form of loss is due to the nature of the core material, and is inversely proportional to the transparency of the material. In some materials, absorption losses may not be uniform across the entire light spectrum, but may instead be wavelength sensitive.

Coupling Losses. Another form of loss is due to coupling systems. All couplings have an associated loss. Several different losses of this sort are identified.

Mismatched Fiber Diameters. This form of loss is due to coupling a large-diameter fiber (D_L) to a small-diameter fiber (D_S) so that the larger fiber transmits to the smaller one. In decibel form, this loss is expressed by:

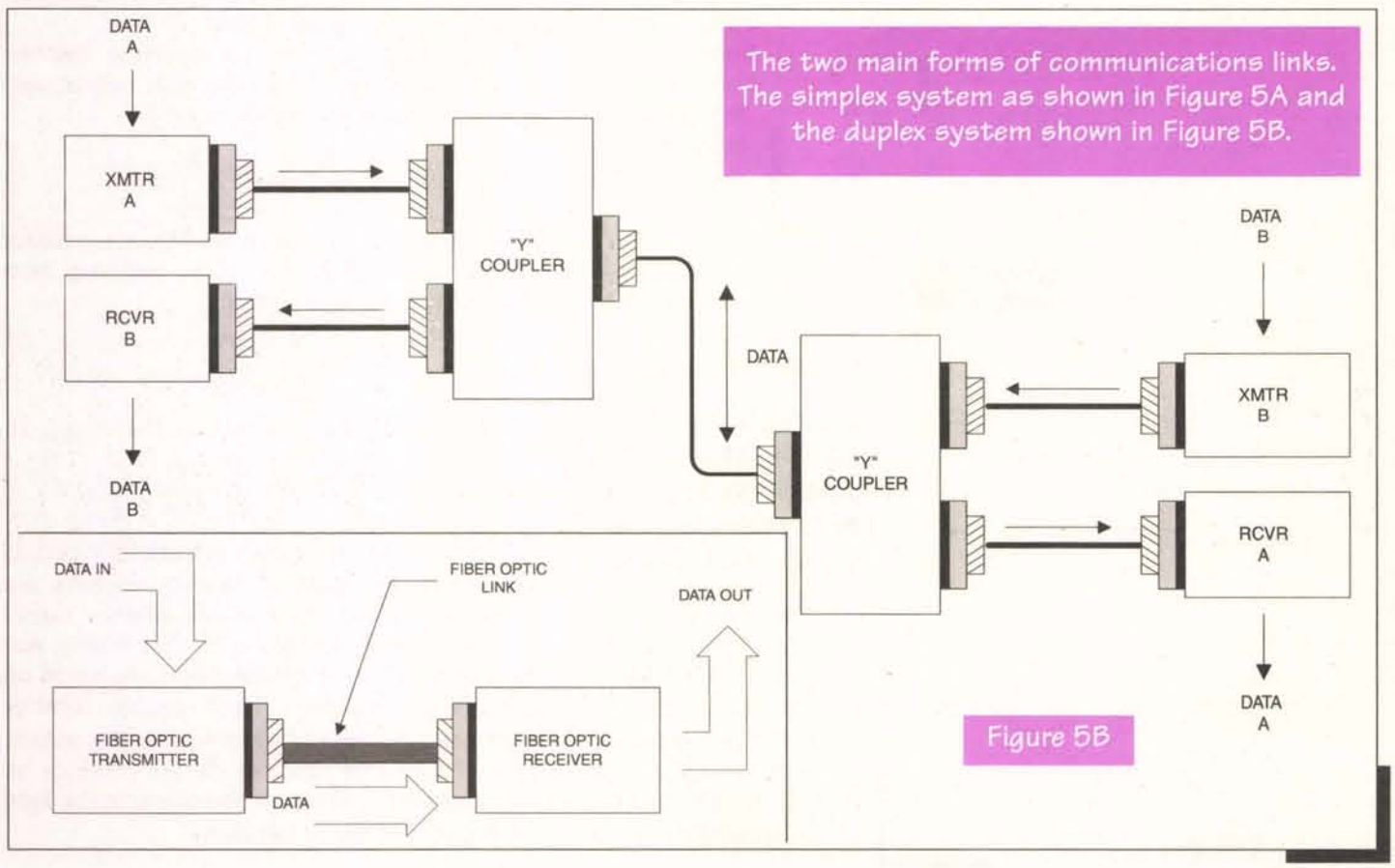
$$dB = -10 \log \left(\frac{D_S}{D_L} \right)$$

Numerical Aperture Coupling Losses. Another form of coupling loss occurs when the numerical apertures of the two fibers are mismatched. If NA_r is the numerical aperture of the receiving fiber, and NA_t is the numerical aperture of the transmitting fiber, then the loss is expressed as:

$$dB = -10 \log \left(\frac{NA_r}{NA_t} \right)$$

Fresnel Reflection Losses. These losses occur at the interface of an optical fiber with air (Figure 4A), and are due to the large change in index of refraction between glass and air. There are actually two losses to consider: the loss caused by internal reflection from the inner surface of the interface, and that caused by reflection from the opposite surface across the air gap in the coupling. Typically, the internal reflection loss is on the order of four percent, while the external reflection loss is about eight percent.

Any form of reflection in a transmission system may be modeled similarly to the modeling of reflections in a



The two main forms of communications links. The simplex system as shown in Figure 5A and the duplex system shown in Figure 5B.

Figure 5B

Fiber Optic Technology — Part 2

radio transmission line. Studying standing waves and related subjects in books on RF systems can yield some understanding of these problems. The amount of reflection in coupled optical systems uses similar arithmetic:

$$\Gamma = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2$$

where,

Γ is the coefficient of reflection,

n_1 is the index of refraction for the receiving material,

n_2 is the index of refraction for the transmitting material.

The mismatching of refractive indices is analogous to the mismatch of impedance problems seen in transmission line systems, and the cure is also analogous. Where a transmission line uses an impedance matching coupling device, an optical fiber will use a coupler that matches the "optical impedances," the indices of refraction. Figure 4B shows a coupling between the ends of two fibers (lenses may or may not be used, depending on the system) made with a liquid or gel having an index of refraction similar to that of the fibers. The reflection losses are thereby reduced or even eliminated.

FIBER OPTIC COMMUNICATIONS SYSTEMS

A communications system requires an information signal source (such as voice, music, digital data, or an analog voltage representing a physical parameter), a transmitter, a propagation medium (in this case, optical fibers), a receiver, and an output. In addition, the transmitter may include any of several different forms of encoder or modulator, and the receiver may contain a decoder or demodulator.

Figure 5 shows two main forms of communications link. The simplex system is shown in Figure 5A. In this system, a single transmitter sends information over the path in only one direction to a receiver set at the other end. The receiver cannot reply or otherwise send data back the other way. The simplex system requires only a single transmitter and a single receiver per channel.

A duplex system (Figure 5B) is able to simultaneously send data in both directions, allowing both send and receive capability at each end. The duplex system requires a receiver, a transmitter, and a two-way beam splitting Y-coupler at each end.

Figure 6A

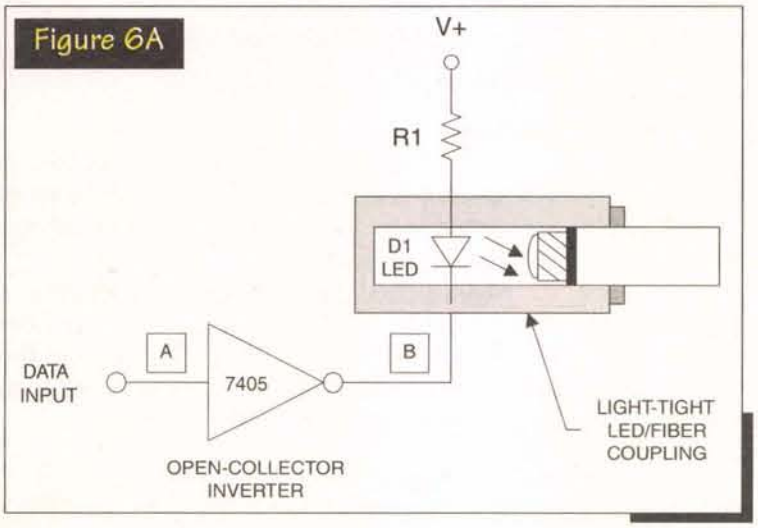


Figure 6B

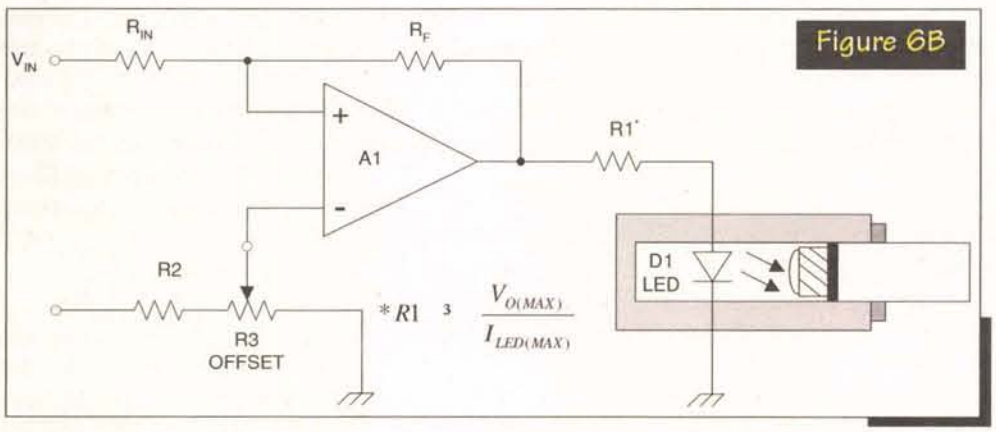
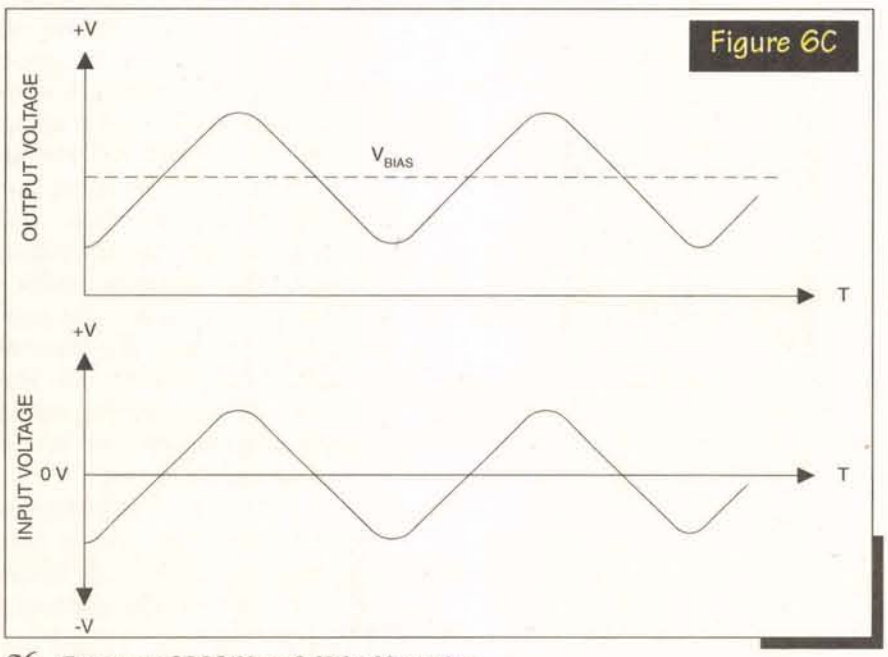


Figure 6C



RECEIVER AMPLIFIER AND TRANSMITTER DRIVER CIRCUITS

Before an optical fiber system is useful for communications, a means must be provided to convert electrical (analog or digital) signals into light beams. Also necessary is a means for converting the light beams back into electrical signals. These jobs are done by driver and receiver preamplifier circuits, respectively.

Figure 6 shows two possible driver circuits. Both circuits use light-emitting diodes (LEDs) as the light source. The circuit in Figure 6A is useful for digital data communications. These signals are characterized by on/off (HIGH/LOW or 1/0) states in which the LED is either ON or OFF, indicating which of the two possible binary digits is required at the moment.

The driver circuit consists of an open-collector digital inverter device in a light-tight container. These devices obey a very simple rule: If the input A is HIGH, then the output B is LOW, and vice versa. Thus, when the input data signal is HIGH, the cathode of the LED is grounded, and the LED turns on and sends a light beam along the optical fiber. When the input data line is LOW, the LED is ungrounded (and therefore turned off), so no light enters the fiber. The resistor R1 is used to limit the current flowing in the LED to a safe value. Its resistance is found from Ohm's law and the maximum allowable LED current:

$$R1 = \frac{(V+) - 0.7}{I_{max}}$$

An analog driver circuit suitable for voice and instrumentation signals is shown in Figure 6B. This circuit is based on the operational amplifier. There are two aspects to this circuit: the signal path and the DC offset bias. The offset bias is needed to place the output voltage at a point where the LED is lighted at about one-half of its maximum brilliance when the input voltage V_{in} is zero. That way, negative polarity signals will reduce the LED brightness, but won't turn it off (see Figure 6C). In other words, biasing avoids clipping off the negative peaks. If the expected signals are monopolar, then V1 should be set to barely turn on the LED when the input signal is zero.

The signal V_{in} sees an inverting follower with a gain of $-R_{if}/R_{in}$, so the total output voltage (accounting for the DC bias) is:

$$V_o = \left(\frac{-V_{in} R_f}{R_{in}} \right) + V1 \left(\frac{R_f}{R_{in}} + 1 \right)$$

Because the network R2/R3 is a resistor voltage divider, the value of V1 will vary from zero volts to a maximum of:

$$V1 = \frac{(V+) R3}{R2 + R3}$$

Therefore, we may conclude that $V_{o(max)}$ is:

$$V_{o(\max)} = \left(\frac{-V_{in} R_f}{R_{in}} \right) + \left(\frac{(V+) R3}{R2 + R3} \right) \left(\frac{R_f}{R_{in}} + 1 \right)$$

Three different receiver preamplifier circuits are shown in Figure 7: analog versions are shown in Figures. 7A and 7B, while a digital version is shown in Figure 7C. The analog versions of the receiver preamplifiers are based on operational amplifiers. Both analog receiver preamplifiers use a photodiode as the sensor. These PN or PIN junction diodes produce an output current I_o that is proportional to the light shining on the diode junction.

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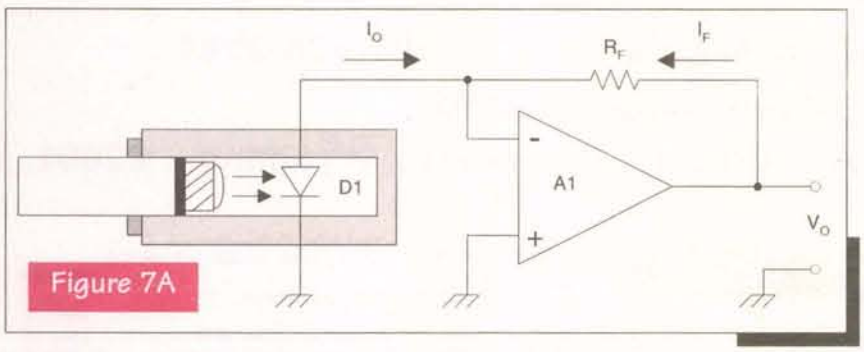

Figure 7A

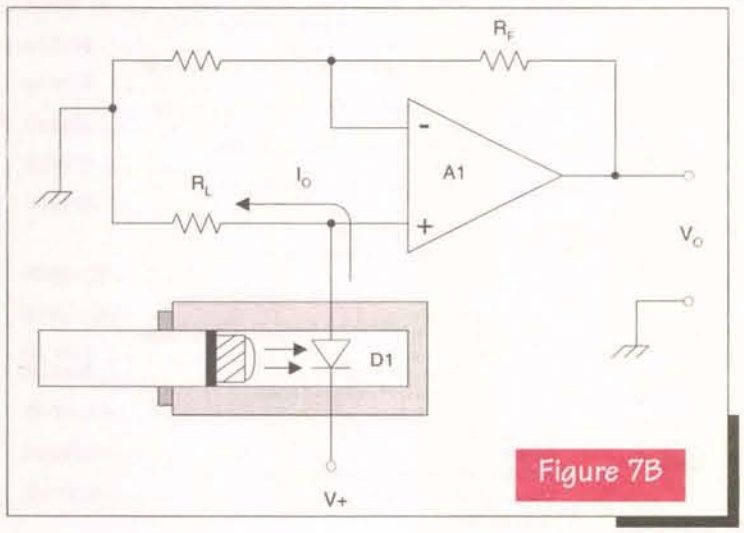

Figure 7B

The version shown in Figure 7A is based on the inverting follower circuit. The diode is connected with its noninverting input grounded, thereby set to zero volts potential, and the diode current is applied to the inverting input. The feedback current I_f exactly balances the diode current, so the output voltage will be:

$$V_o = -I_o R_f$$

The noninverting follower version shown in Figure 7B uses the diode current to produce a proportional voltage drop (V1) across a load resistance R_L. The output voltage for this circuit is:

$$V_o = I_o R_L \left(\frac{R_f}{R_{in}} + 1 \right)$$

Both analog circuits will respond to digital signals, but they are not optimum for that type of signal. Digital signals will have to be reconstructed because of uncertainties caused by dispersion. A better circuit is that of Figure 7C, in which the sensor is a phototransistor connected in the common emitter configuration. When light shines on the base region, the transistor conducts, causing its collector to be at a potential only a few tenths of a volt above ground. Conversely, when there is no light shining on the base, the collector of the transistor is at a potential close to V+, the power supply potential.

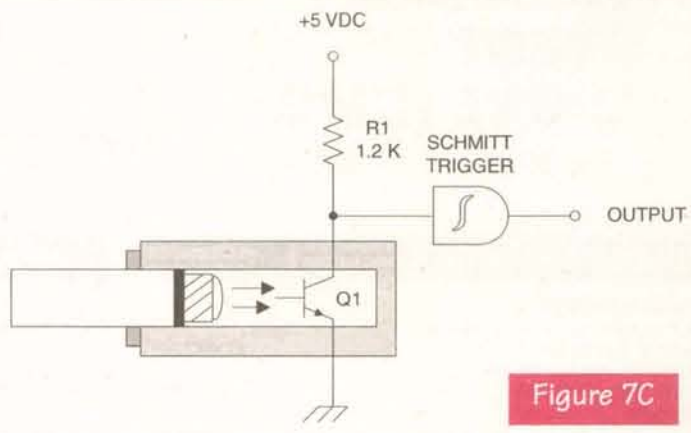

Figure 7C

Clean-up action occurs in the following stage, a digital Schmitt trigger. The output of such a device will snap HIGH when the input voltage exceeds a certain minimum threshold, and remain HIGH until the input voltage drops below another threshold (snap-HIGH and snap-LOW thresholds are not equal). Thus, the output of the Schmitt trigger is a clean digital signal, even though the sensed signal may be blurred. **NV**

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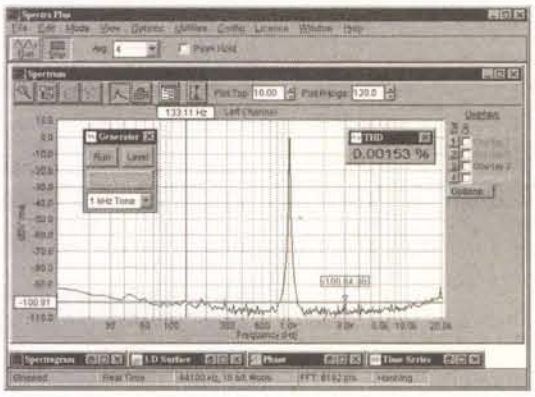

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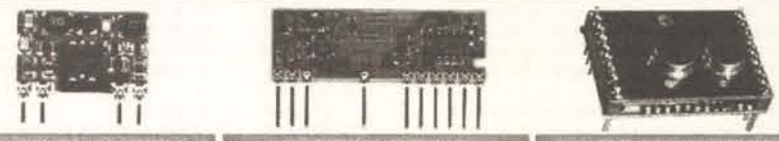

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